ME-85-01

Pavement Surface Temperature Study - Winter 1983 - 84

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Ministry of
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Branch

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Abstract:

As one phase of a study to determine the cost-benefit of salt versus a sand/salt mix for pavement de-icing, twenty-one thermocouples were installed at four highway sites in the Toronto area to measure pavement temperatures.

These measurements were correlated with traffic volumes, solar radiation, ambient air temperature, and other environmental factors.

The results indicate that the pavement temperature is generally affected by solar radiation and ambient air temperature; however there is no evidence that the pavement temperatures in the wheel tracks are affected by traffic.

Key Words: salt, pavement, temperature, thermocouples

Comments:

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1. INTRODUCTION

During the winter of 1983-84, a 'Preferred Salt Option Study' was carried out in District 6, Toronto by Mr. D. Aspinwall, Maintenance Engineer. The intent of the study was to determine if a cost benefit could be realized with the adoption of a winter maintenance procedure that placed emphasis on the use of straight salt, rather than a sand/salt mix, for pavement deicing purposes. The study's mandate included ascertaining the effectiveness of pure salt to clear highways of ice and snow at lower temperatures. The District proposed that pavement surface temperatures be studied with the use of thermocouples installed in the pavement at various highway locations as part of a separate study to determine the influence of temperature on the clearing operation.

Installation of the thermocouples was carried out by the Research and Development Branch at four sites selected by Mr. D. Wilson, Toronto District. The Research and Development Branch was to produce a report evaluating the Winter Maintenance Procedure M-700-C. As stated in the general guidelines of MTC Operating Instruction M-700-C, from the manual 'Winter Maintenance Operations During Winter Seasons':

> As the temperature gets lower, the effectiveness of the salt decreases until it becomes ineffective.
>
> Normally, salt should not be applied when the temperature is below $-12^{o}C$. However, in the presence of sun and heavy traffic volume which create a higher road surface temperature, salt can be effective down to a temperature of $-18^{o}C$. (1)

The objective of the pavement temperature study carried out by the Research and Development Branch was to analyze the temperature data and attempt to correlate the road surface temperature with traffic volumes, ambient air temperature, solar radiation, and other environmental factors in order to

re-evaluate present standards concerning the effectiveness of deicing salt at lower air temperatures.

The District designed this experiment to measure pavement and air temperatures on three selected freeways (Hwy 401, QEW (Hwy 451), and Hwy 400) with high, medium, and lower traffic volumes respectively. A fourth site (Hwy 401/409) was used as a control site, testing the experimental procedure.

2. TEST SITES

2.1 Site Locations

The following highway sites were selected to install the thermocouples and automatic recording instrumentation (except as noted):

- Highway 401 westbound collector driving lane with AADT of 238,600 (permanent counting station - Keele).
- QEW eastbound driving lane with AADT of 86,400 (FTMS box - Ford Drive).
- Highway 400 southbound driving lane with AADT of 48,400 (permanent counting station - Maple).
- Highway 401/409 interchange, Highway 401 westbound passing lane with an AADT of 174,000 adjacent asphalt and concrete sections were used for comparison at this site (manual recording).

At Highway 401/409, the pavement temperature was measured using copper-constantan thermocouples by a hand held mini mite potentiometer every six hours by field inspectors. The field data sheets were sent to the Research and Development Branch for visual inspection to judge if the readings were reasonable. This monitoring function served as the warning signal to determine if the pavement temperature study conducted during the winter of 1983-84 would produce worthwhile results. All the equipment was installed within a 2-3 day period in December 1983. The intent of the Highway 401/409 site was that it would indicate if the entire study should be terminated early due to poor results.

2.2 Instrumentation

The thermocouple wire used was T-type copper-constantan with a teflon coating with a range of $-68^{o}C$ to $+204^{o}C$. The standard limits of error (accuracy) is $\pm$ $1^{o}C$. Quicktip type thermocouple pressure connectors were used. The wires were placed in the quicktip and then clamped into a hexagon shape which became

the junction point. All the thermocouples were calibrated to ensure they were functioning properly before installation. All the thermocouple wires at each site were of equal length to reduce errors.

The pavement thermocouple installation procedure was as follows:
A groove of 6mm (1/4") width by 25mm (1") depth was transversely sawed across the pavement from the driving lane to the paved shoulder. Three holes of 3mm (1/8") diameter were drilled at a slight angle to a 6mm (1/4") depth below the pavement surface in the centre of the wheel track, between the wheel tracks, and in the paved shoulder (Figure 1). The quicktip of each thermocouple was snugly fitted into the drilled hole; however, there may have been air gaps between the quicktip and the asphalt. The wires were buried into the cut groove and then covered with bituminous mastic material (Figure 2). The thermocouple used to measure the exposed air temperature was installed above the ground approximately 150mm above the eaves of the traffic hut (PCS) and the thermocouple for shaded air temperature was located under the eaves of the hut. The thermocouple wires were passed through a small round window screen inside the traffic hut and connected to the strip chart recorder or data-logger automatic temperature recorder to monitor the pavement and air temperatures. The traffic hut was normally heated during the winter months to ensure proper functioning of all the counting and recording equipment.

Mr. F. Holt of the Materials and Engineering Systems Section (R & D Branch) installed five thermocouples in each site at the selected locations. The thermocouples were installed on short notice in mid-December, 1983 in very cold weather because the District was anxious for this phase of the study to encompass the entire 83/84 winter. Due to the short lead time following a request for installation, no laboratory tests nor review of instrumentation

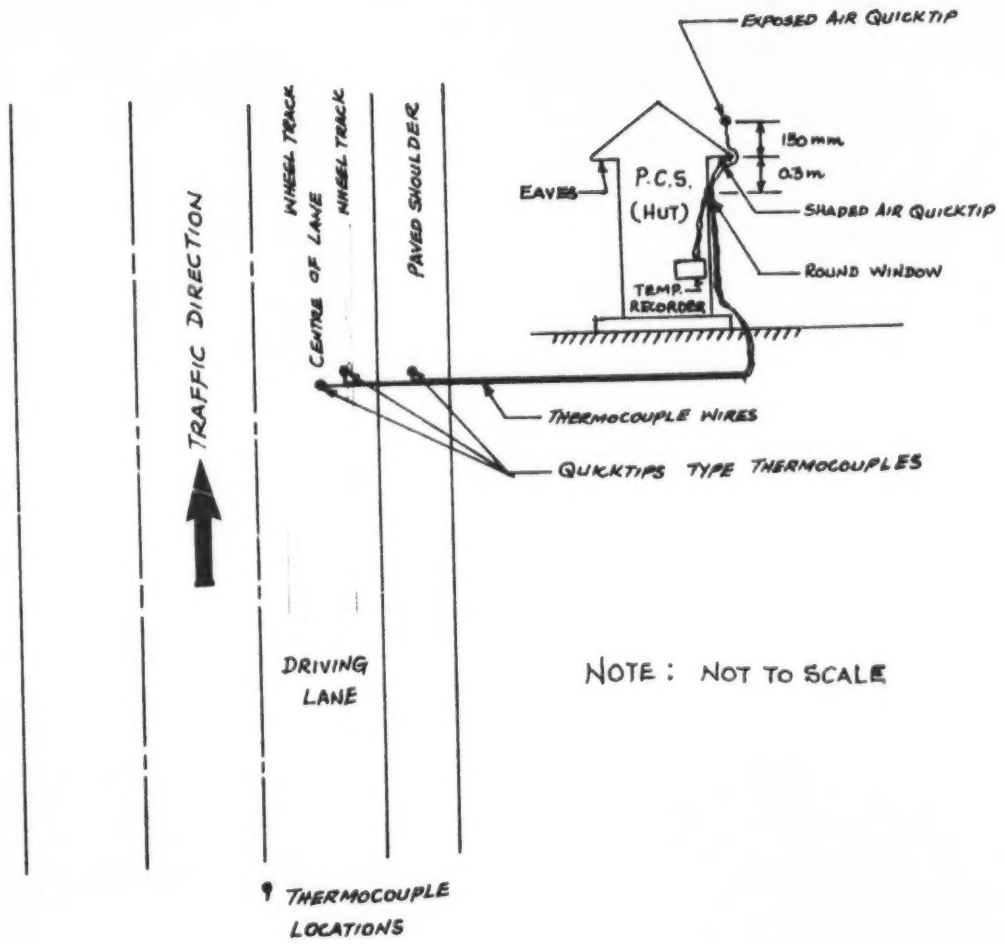
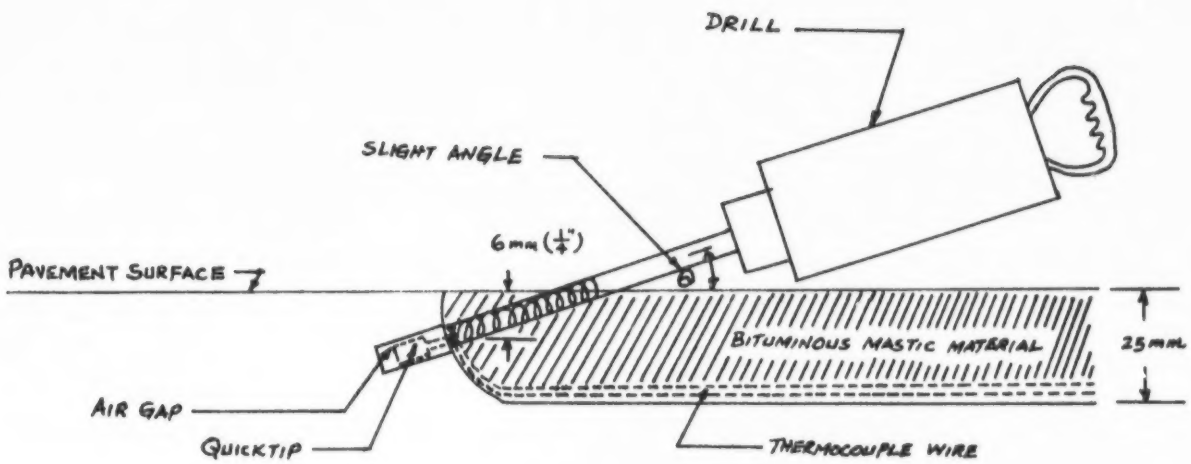


Figure 1 Typical Site Layout for Thermocouples



NOTE: NOT TO SCALE

Figure 2 Thermocouple Installation in Pavement

procedures were conducted on the equipment installed and the system error was unknown but assumed to be no more than $\pm 0.5^{o}C$.

2.3 Factors Affecting Pavement Temperatures

Since the completion of the temperature measurements in April 1984, information has been obtained from the literature about other factors which significantly influence the pavement temperature.

2.3.1 Solar Radiation

As quoted in P.M. Noss, 'The Relationship Between Meteorological Factors and Pavement Temperature', Symposium on Frost Action on Roads, Paris 1973 (2)

> In order to study the heat exchange processes at the pavement surface, it is necessary to know the amount of solar and atmospheric short-and-long-wave radiation, the distribution of wind and temperature in the air, the temperatures, and the properties of soils below the surface. Further, the surface temperature is affected by precipitation, evaporation and condensation, the formation of ice, cloud cover and fog. An illustration of the different fractors involved in the balance is shown in Figure 3.

Solar radiation is a very significant factor, but it was not measured at the test site. Instead, the information was obtained from the Toronto and Woodbridge climatological stations monitored by Environment Canada. These are the closest stations to the test sites. The equipment to measure solar radiation at each of the sites, and the expertise involved, was not available within the Ministry.

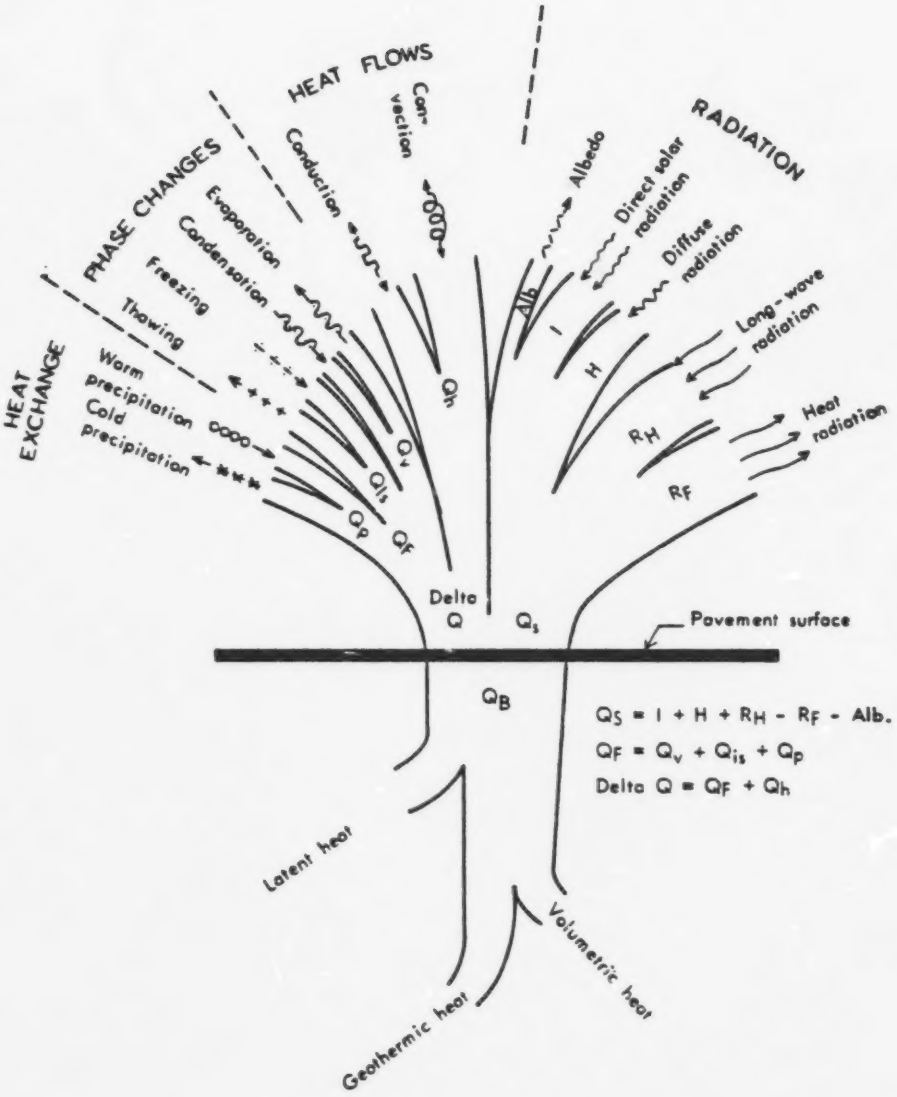


Figure 3 Heat Balance at the Pavement Surface (taken from Ref. (2))

2.3.2 Construction Materials

As quoted in Kent Gustafson 'Icing Conditions on Different Pavement Structures', Transportation Research Record 860 (3)

> It is the energy balance and primarily the radiation balance that govern the variation of surface temperature on a road. The temperature of the road surface is affected both by climatic action on the surface such as radiation and precipitation and by heat exchange with the underlying soil strata. Chiefly by conduction, movement of heat takes place in the road structure to or from the road surface. The temperatures prevailing in the road structure depend, among other things, on road construction and the road materials used. The thermal conductivities and heat capacities of the materials have great significance for the variation of temperature on and in a road. For mineral materials, the thermal conductivity largely depends on the density and water content, but also on the conductivities of the constituent minerals. Materials of low density have lower conductivity owing to the fact that there are few points of contact where thermal conduction can take place. Increase in water content results in an increase in conductivity. Ungraded crushed rock of low density contains very little water and therefore, has a lower thermal conductivity than, for instance, gravel or sand.

Gustafson's study has shown that the subgrade's moisture content and soil structure play a key role in determining the thermal conductivity of the substructure. The subgrade's thermal conductivity influences the surface temperature during the night. Comparing the shoulder temperature to the pavement temperature at night, when problems with melting ice occur, may

not be valid due to differences in the subgrade. The frost line also varies under the shoulder, and the closer free water is to the surface, the more heat that is passed to the surface when it freezes at night.

Therefore, a comparison of wheel track to centre of lane pavement temperatures is more valid than comparing these temperatures to pavement shoulder temperatures. Different types of surface courses and pavement structures may also have affected the pavement surface temperatures. Highway 401 at Keele Street was resurfaced with open-graded friction course (OFC) over an old concrete pavement with GBC A base. The QEW at Ford Drive used slag material for the surface course over a GBC A base, and Highway 400 at the Maple site used an HL1 surface course placed over a bituminous base course on GBC A. Therefore, the data for pavement surface temperatures between the three sites cannot be properly related. In addition, Highway 400 was widened from 4 to 6 lanes over the years, such that the shoulder pavement structure is unlikely to be the same as the driving lane pavement structure.

2.3.3 Installation of Pavement Surface Probes

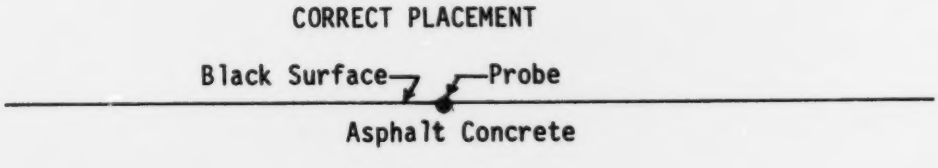
A factor which could produce unknown errors has been identified as the difference in pavement temperatures between the surface and 6mm (1/4") below the surface.

As quoted in Arthur L. Strauh, H.N. Schenck, Jr., and Frank E. Przybycien, 'Bituminous Pavement Temperature Related to Climate', Highway Research Record No. 256 (4)

Correct Installation of Surface Probe -

From this information, it was concluded that the uppermost fraction of 25mm (1") of asphalt concrete sometimes experiences a large temperature gradient. To record the surface temperature, it is necessary to take great care in the location of the probe. Figure 4 shows how

the surface probe should be installed. It is recommended that one part of the thermocouple tip be exposed to the air. Care must be taken that the probe be flush with the pavement surface and that the colour of the exposed tip is the same colour as the asphalt concrete.



Three quarters of the probe tip is surrounded by asphalt concrete and one quarter is surrounded by air.

Figure 4. Installation of Surface Probe (taken from Ref. (4))

Figure 4 from Reference (4) shows a possible method of measuring surface temperature in any future trials or laboratory experiments.

Placement of the thermocouple at 6mm (1/4") below the surface may not have provided accurate surface temperature measurements at our test sites. The Straub study concentrated on temperature differentials in the summer and gave no test results of temperature differentials in the winter. It is possible that the heat generated by tires and pavement interaction is momentary, and the heat could dissipate before reaching the probe at 6mm (1/4") depth. Thus, the placement of the probe may have been too deep to reflect the temperature changes due to traffic. Another possible probe error encountered was difficulty in placing each probe at exactly the same depth below the pavement surface with a hand held drill and the unknown error this may have introduced.

2.3.4 Other Problems

Thermocouples to monitor air temperatures were placed on the traffic huts, located within the right-of-way. In recent discussions with personnel from Environment Canada, it was suggested that the measurements obtained from the exposed and shaded thermocouples would not be valid due to radiation effects. Heat escaping from the traffic huts may have affected the values of the exposed and shaded air temperature measurements. Also long wave radiation (heat) from the earth on both thermocouples and short wave radiation (solar) on the exposed thermocouple affects the temperature reading.

An automatic strip chart recorder was used to record continuous pavement and air temperatures at the Maple and Ford Drive sites from mid December 1983 to mid January 1984. From mid January on, a data logger (model FLU/2240B) was rented to complete the tests; however, this equipment was set up to record temperatures only once per hour.

The use of the strip recorder at the Highway 400/Maple site presented problems in matching the temperatures recorded with the correct time of day due to insufficient time references. Strip chart paper was difficult to obtain and the printing was not clear, which made it difficult to interpret the information. Also, there was slippage of the paper and the recorder was not maintaining the calibrated speed. As a result, a switch was made to the datalogger units about mid-January and their use was continued to mid-April 1984.

3. DATA COLLECTION, INPUT, AND ANALYSIS

3.1 Data Collection

The temperature recording began in mid-December 1983. The strip chart temperature recorders were used at Highway 400/Maple and QEW/Ford Drive sites. Data collection from the Highway 401 site began in mid-January 1984 with a datalogger. Personnel from District 6 Maintenance Office sent in the data tapes regularly to the Research & Development Branch for analysis.

In mid-April 1984 Environment Canada's monthly meteorological summary was obtained from District 6 Maintenance Office. The City of Toronto (Toronto Island Airport) information was used for the Highway 401/Keele site and Lester B. Pearson International Airport information was used for Highway 400/Maple site because the urban and suburban weather conditions were assumed similar with Highways 401 and 400 respectively.

In the month of July a request was made to Environment Canada, Toronto Office, to obtain the solar radiation data (December 1983 to March 1984) in units of megajoules per metre square per hour. This information had to be key-punched into the already key-punched cards for the solar radiation hours (6:00 to 18:00) in mid-August 1984. These data were not available for input at one time. Instead, a piecemeal method was used to input data on a number of occasions (e.g., first input the pavement and air thermocouple temperature data, weather data from airport, traffic data, then solar radiation data, etc.). It was a very time consuming process.

Traffic data were provided by the Program Planning Information Office. Traffic data from Highway 401 W.B. collector driving lane were available as the number of vehicles per lane per hour. Highway 400 S.B. traffic count was recorded in numbers per direction (not by lanes) per hour. Traffic data

for the months of February to April 1984 were unavailable from telemetry, therefore, 1983 data were used instead of 1984 data. Past traffic characteristics were used to establish that approximately 31% of the total traffic volume travelled in the driving lane. The number of vehicles per lane (driving lane) per hour was manually calculated for use as data input. Traffic data from QEW E.B. were not available.

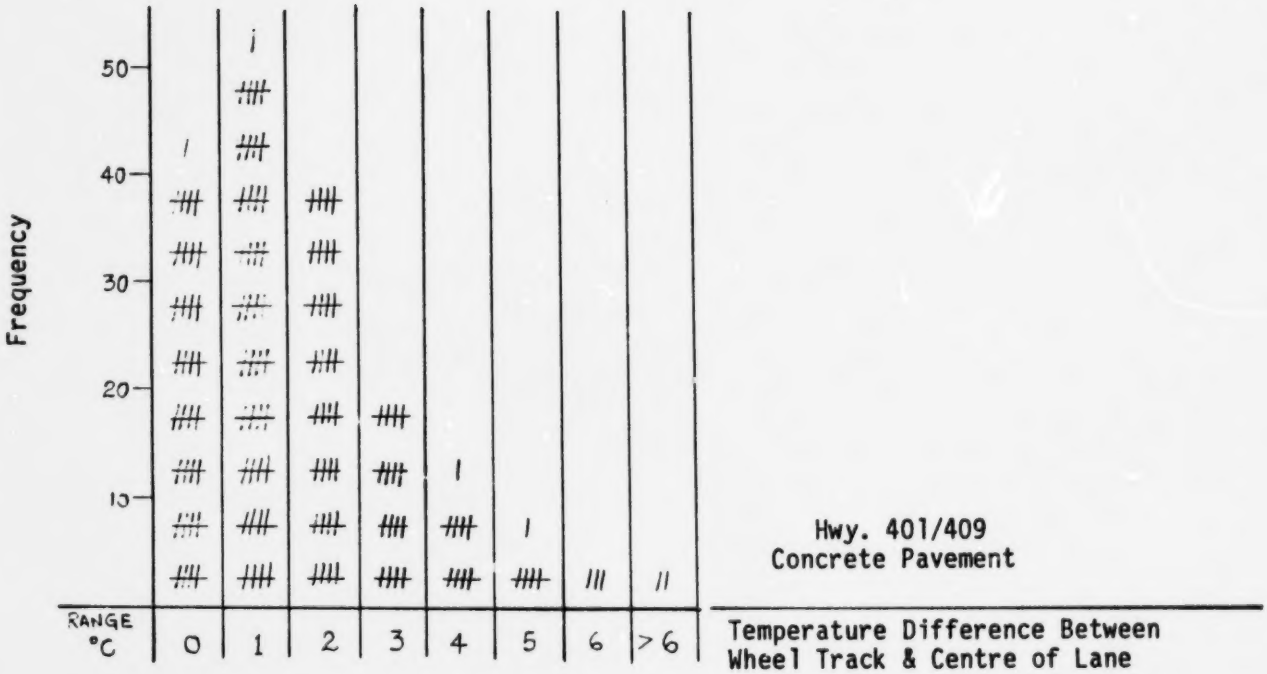
3.2 Data Input

Temperatures obtained from thermocouple measurements, along with traffic and environmental data, were entered on computer cards. Using the Statistical Analysis System (SAS) package, a multiple regression was run on the 19 independent variables and 5 dependent variables. Table 1 lists the variables used in the analysis (Appendix A).

3.3 Data Analysis

The data from the test site at Highway 401/409 have been visually analyzed and tallied into a histogram (Figure 5), which shows a similar frequency distribution pattern of temperature differences between wheel track and centre of lane for concrete and asphalt pavements. The data were plotted on continuous graph paper. The curves showed some relationship between the five thermocouples as they usually varied in the same pattern. Some points on the continuous plot showed unexplainably large deviations from the other points. The source of error may have resulted from the incorrect connections of the thermocouple leads to the mini mite meter terminal, i.e. putting the copper lead on the negative terminal.

The data from the test sites, Traffic Office, and Environment Canada were analyzed to correlate the road surface temperature with traffic volume, ambient air temperature, solar radiation, and other environmental factors by the Statistical Analysis System (SAS) package. The time frame from the



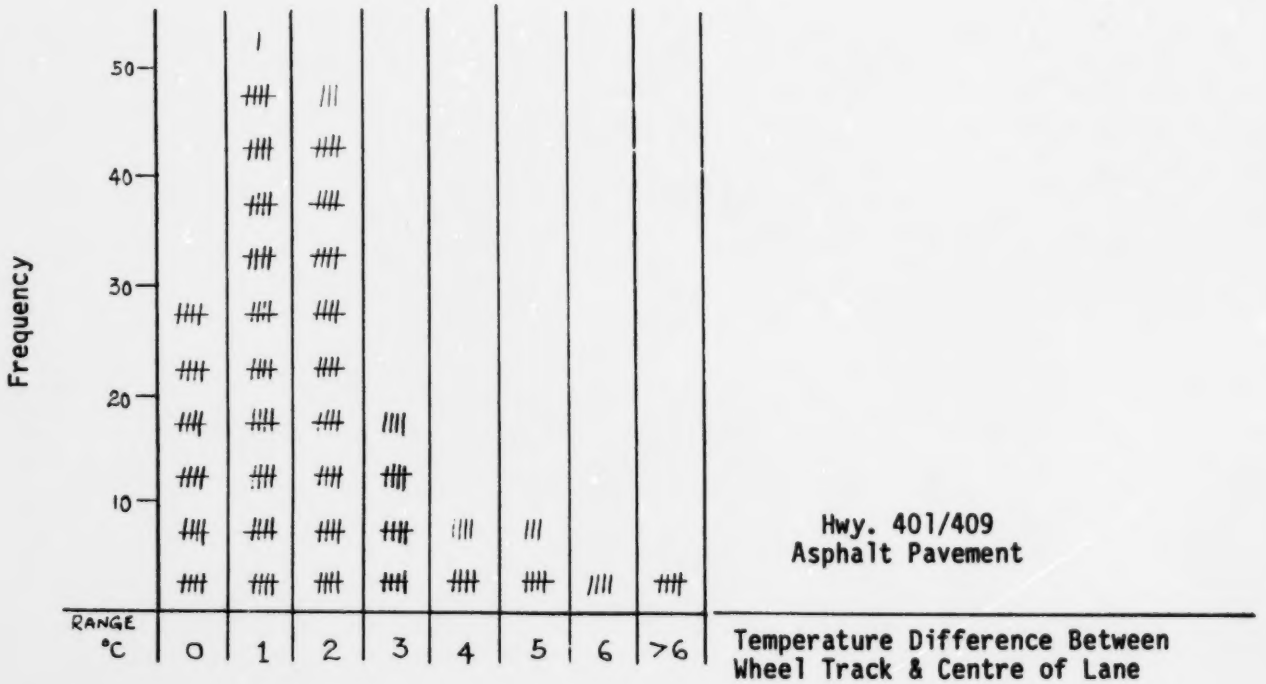


Figure 5 Temperature Difference Between Wheel Track and Centre of Lane

data analysis was limited to solar hours (6:00 to 18:00) to determine if the morning and afternoon traffic peaks had any effect on the wheel track pavement surface temperature. Initially 19 independent variables were used. Later this was reduced to 14 variables because some independent variables were found to be biased and not independent by computer X'X Matrix analysis. Refer to Appendix A, multiple regression analysis output where the letter 'B' indicates a bias.

4. THEORY OF VAPOUR PRESSURE

Water freezes when its vapour pressure exceeds that of ice. Water's vapour pressure varies with temperature and decreases as the temperature decreases. Ice vapour pressure increases as temperature increases, but at a different rate than water. Below $0^{o}C$ pure ice has a lower vapour pressure than pure water and the opposite is true above $0^{o}C$. A substance always seeks the lowest energy state; therefore, water will be in phase with the lowest vapour pressure. As the vapour pressure is temperature dependent, then the phase (ice and water) depends on temperature also (Figure 6).

Addition of salt to water creates a brine solution which exhibits a lower vapour pressure than pure water if both solutions are at the same temperature. Therefore, the brine solution must reach a lower temperature than pure water for it's vapour pressure to exceed that of ice and for freezing to occur.

The factors which determine the effectiveness of salt are the temperature of the ice and its corresponding vapour pressure coupled with the percentage of salt by weight in the solution and its corresponding vapour pressure. Salt will have no effect on ice at or below $-21.1^{o}C$ and just above $-21.1^{o}C$, 23.3% salt is needed. Such a high percentage of salt would be both damaging to the environment and expensive (Figure 7).

The temperature of the ice and salt is determined by both the air and pavement temperatures. The temperature of the brine solution determines its effectiveness and thus it is important to ascertain what determines its temperature. If salt is applied to the road during a storm before ice or packed snow has formed, the salt will form a brine which will quickly percolate to the pavement surface. The brine formed will be in contact with the road surface and will probably be mainly a function of the surface temperature of the road.

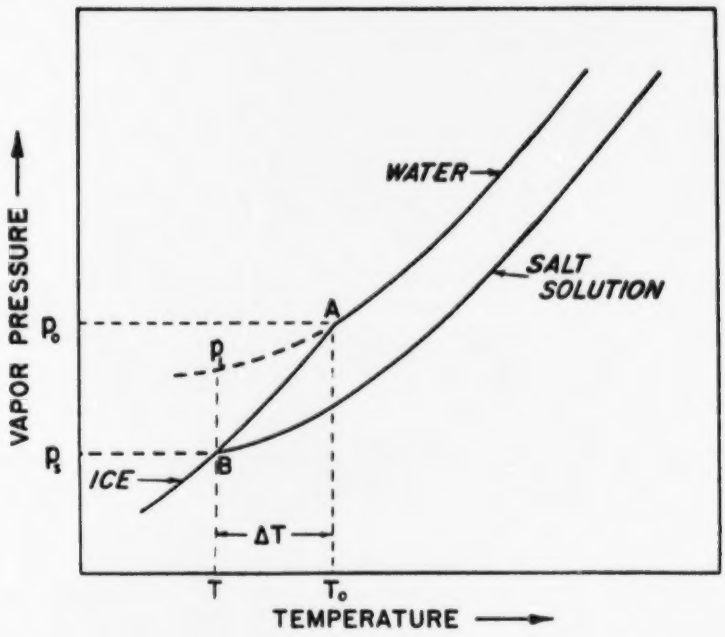


Figure 6 Thermodynamic Relationship in Melting of Ice by Chemicals (taken from Ref. (5))

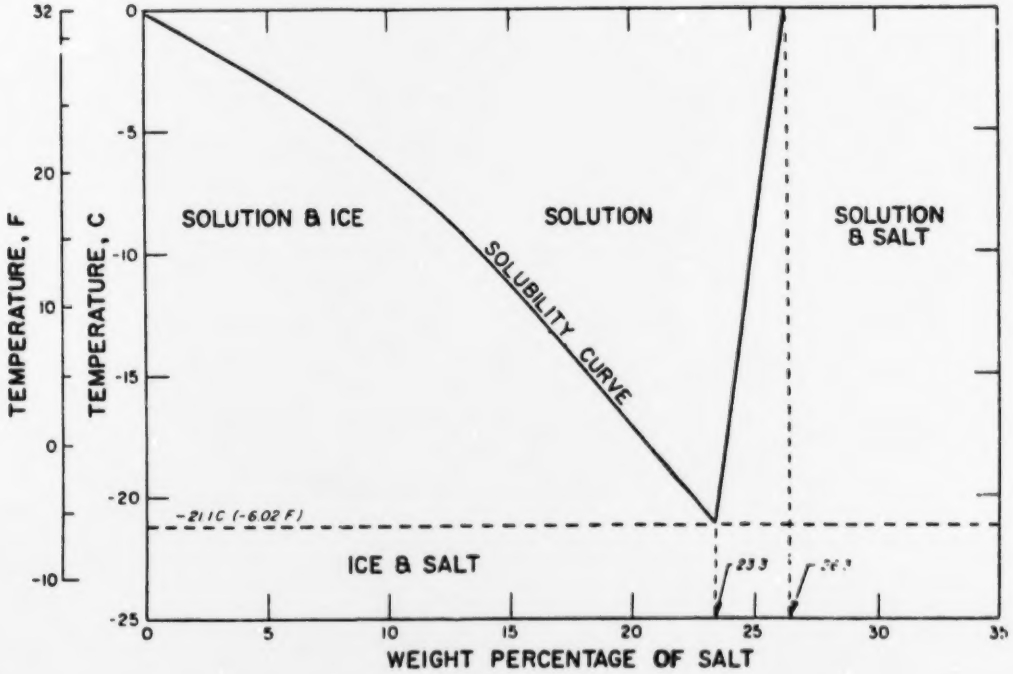


Figure 7 Phase Diagram for Water-Rock Salt (taken from Ref. (5))

If salt is applied to remove packed snow or ice, its ability to form a brine solution on the surface of the ice will be affected by the air temperature. The composite effect of the road and air temperatures in determining the ice or snow temperature is complex. There are several possibilities which need to be evaluated. Does a road covered with ice or packed snow act as a bare road does on a cloudy day, i.e., when the road temperature corresponds closely to the air temperature? Or does the snow and ice insulate the road and raise or maintain its temperature with the influence of heat radiated from the subgrade?

5. RESULTS AND DISCUSSION

The data from the test site at Highway 401/409 seemed to indicate that the asphalt surface temperature was usually lower than the concrete surface temperature. This is contrary to expectation. Black pavement should absorb more solar radiation and thus should be warmer than concrete, which is white. There appears to be considerable experimental error in this data and thus it must be ignored.

The multiple regression analysis (Table 2 in Appendix A) indicated that wheel track temperature showed some correlation with the exposed air temperature (test site thermocouple temperature) and solar radiation (megajoules/m^2/h) with the coefficient of determination R^2 ranging from 0.88 to 0.94. It also showed that wheel track temperature correlated without significance with traffic volumes (one independent variable), with R-Square ranging from 0.002 to 0.07 (see * sign on Table 2 in Appendix A). The term R-Square R^2 measures how much variation in the dependent variable can be accounted for by the model. R^2, which can range from 0 to 1, is the ratio of the sum of the squares for the model divided by the sum of the squares for the corrected total. In general, the larger the value of R^2, the better the model's fit.

With the degree of experimental error involved, it cannot be discerned if there is any increase in wheel track temperature as a result of traffic. The shoulder, wheel track, and centre of lane temperatures are essentially the same, all varying from each other within the limit of experimental error. They are, therefore, considered equal and only the pattern of their joint high and low peaks was considered (Table 3 in Appendix A).

A key objective of this study was to determine the effects of traffic on pavement temperature. At present, the standards allow for salting at lower temperatures (down to -18°C) if there is heavy traffic. This rule is based on experience. Initially, it was assumed that the tires transferred some heat to the pavement at the tire tracks. However, heavy traffic could also affect the salt or brine by working it through the snow or by applying pressure through compaction and thereby melting the snow.

Figure 8 indicates solar radiation measured on typical overcast, cloudy, and sunny days, while Figures 9a,b,c show the corresponding pavement and air temperatures respectively.

It can be seen from Figure 9c that the pavement surface temperature peaks in the early afternoon on a sunny day. The pavement temperature will exceed the air temperature on a sunny day. A comparison of two different days receiving about the same amount of solar energy reveals that the peak pavement temperatures will be almost the same. Air temperatures will also rise, but the air absorbs very little solar radiation and is heated mainly from radiation from the earth. Air temperatures therefore, rise less than the black asphalt pavement temperatures. It can also be seen that the air temperature on a sunny day is directly related to solar radiation. When a correlational analysis is performed, solar radiation and air temperature cannot be considered as two independent variables. The air temperature must be dropped from the analysis, at least on sunny days.

Observation of Figure 9a shows that pavement temperatures closely parallel the air temperatures on overcast days. During the day, the temperatures are almost the same. Solar radiation has minimal influence on the pavement and air temperatures. As the air mass moves, it fluxtuates in temperature and the

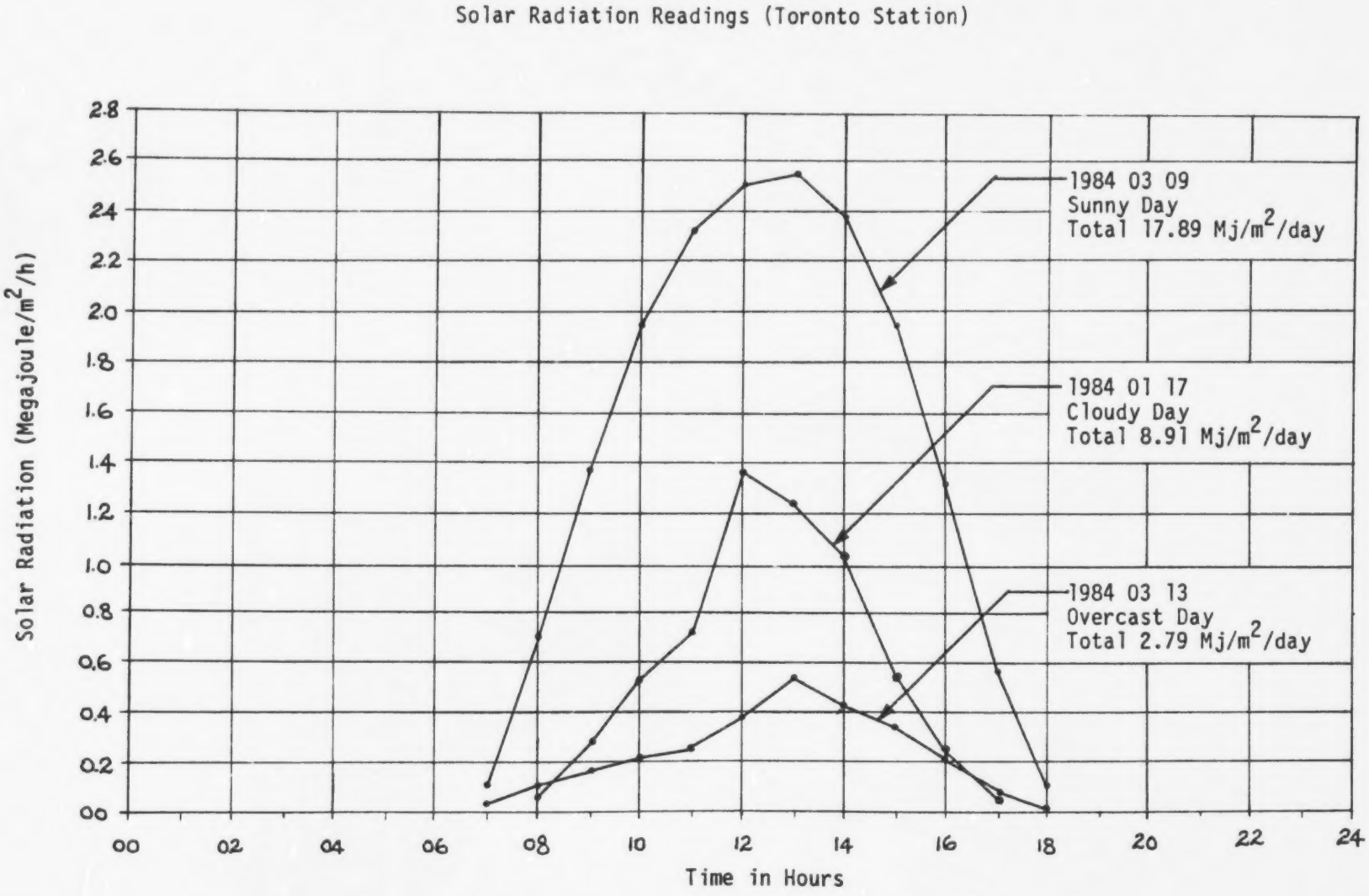


Figure 8 Effect of Cloud on Solar Radiation Received

Thermocouple Readings on 1984 03 13 (Overcast Day)

(Hwy 401 - Keele St.)

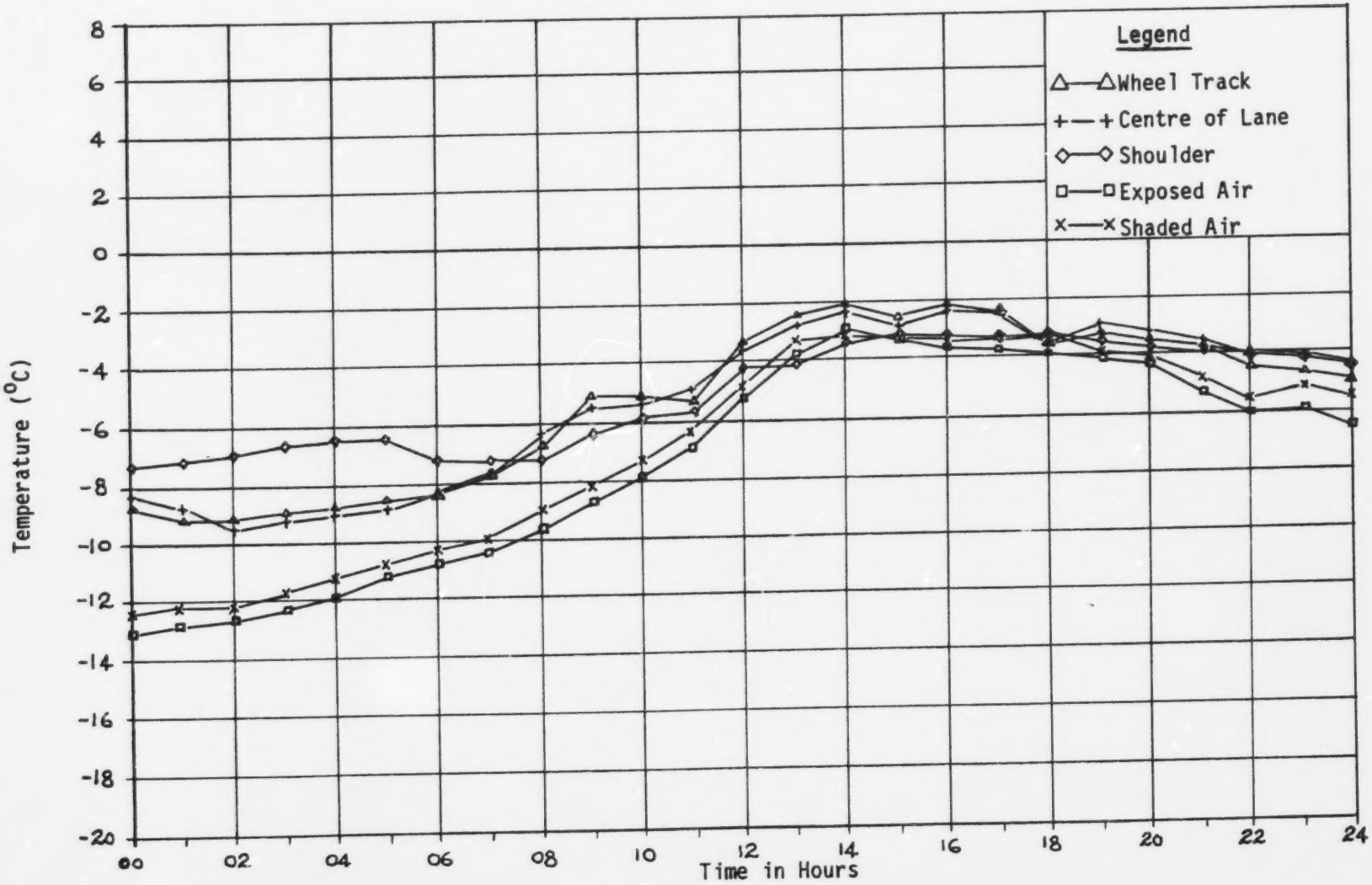


Figure 9a Daily Pavement Temperatures
- Low Solar Radiation (total 2.79 Mj/m^2/day)

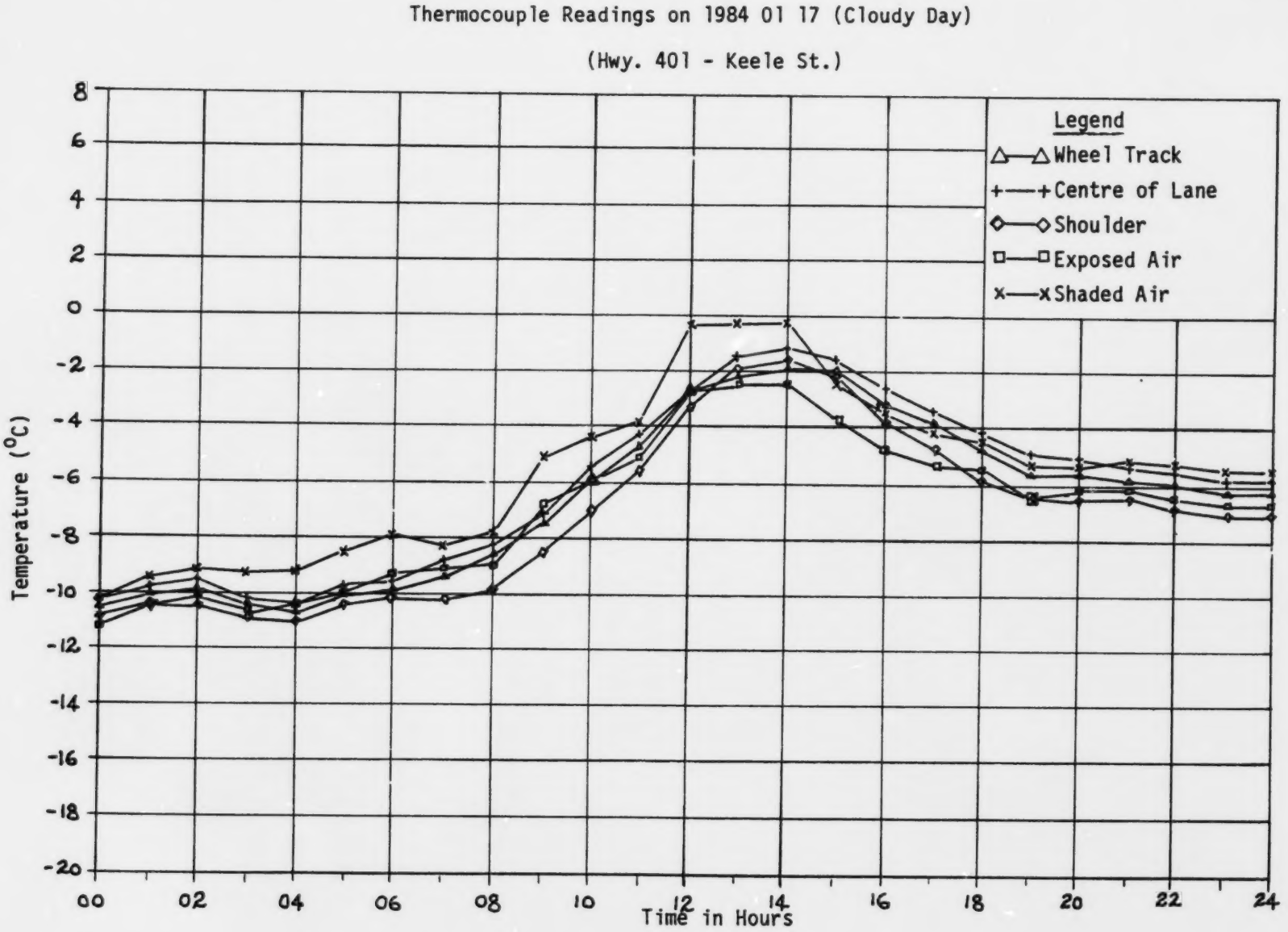


Figure 9b Daily Pavement Temperatures
- Medium Solar Radiation (total 8.91 Mj/m^2/day)

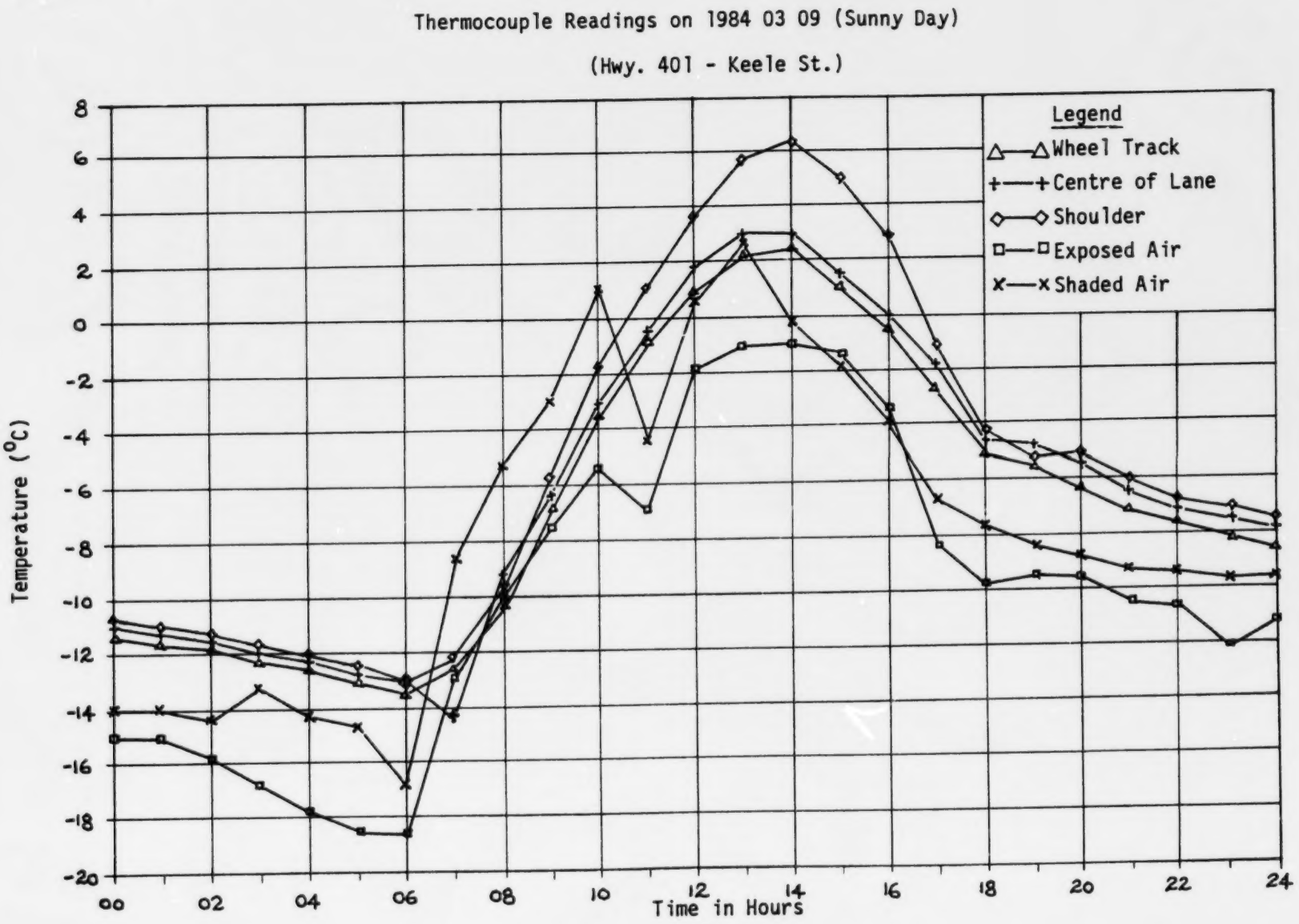


Figure 9c Daily Pavement Temperatures
- High Solar Radiation (total 17.89 Mj/m^2/day)

pavement temperature responds as well. The air temperature is fluctuating due to global movements of air masses and not due to local solar radiation. Therefore, on overcast days, the pavement temperatures will correlate closely with air temperatures.

Comparing the peaks in traffic flow (Figure 10) for Keele Street (Hwy. 401) with pavement temperatures shows that there is no noticeable rise in pavement temperature during peak traffic volumes. However, temperatures were recorded on an hourly basis and some small increases in wheel track temperatures may have occurred between the hourly readings.

This study should be redirected to a general objective of determining under what conditions, environmental and otherwise, salt will be effective.

The study could be directed into several areas using the following lines of inquisition:

1.0) At what temperature and in what practical concentration does salt work? (Source - from literature)

2.0) What determines the temperature at which salt acts? (laboratory and literature)

  2.1) If salt is applied during a snow storm, what temperature is the snow and what effect does it have on the salt melting ability? (laboratory and literature)

  2.2) What is the inter-relationship between the snow or ice temperature and the pavement and air temperature?

  2.3) If salt is placed on the surface of the ice or packed snow, what determines the surface temperature of the packed snow, the pavement or the air temperature? (laboratory)

3.0) If salt is applied during a snow storm, the pavement surface will not be receiving solar radiation. How close to the air temperature will the pavement temperature be? Will it be similar to a cloudy day where pavement temperature fluctuates in a parallel sequence with the variations in air temperature? (field and laboratory)

4.0) At night, how cold does asphalt get and what is its dependence on air temperature and the type of subgrade material? (field)

5.0) Does slow traffic radiate heat and, if so, how much? (field)

6.0) Is it the effect of tire pressure on the snow which causes melting or is it the heat given off by the tires to the asphalt?

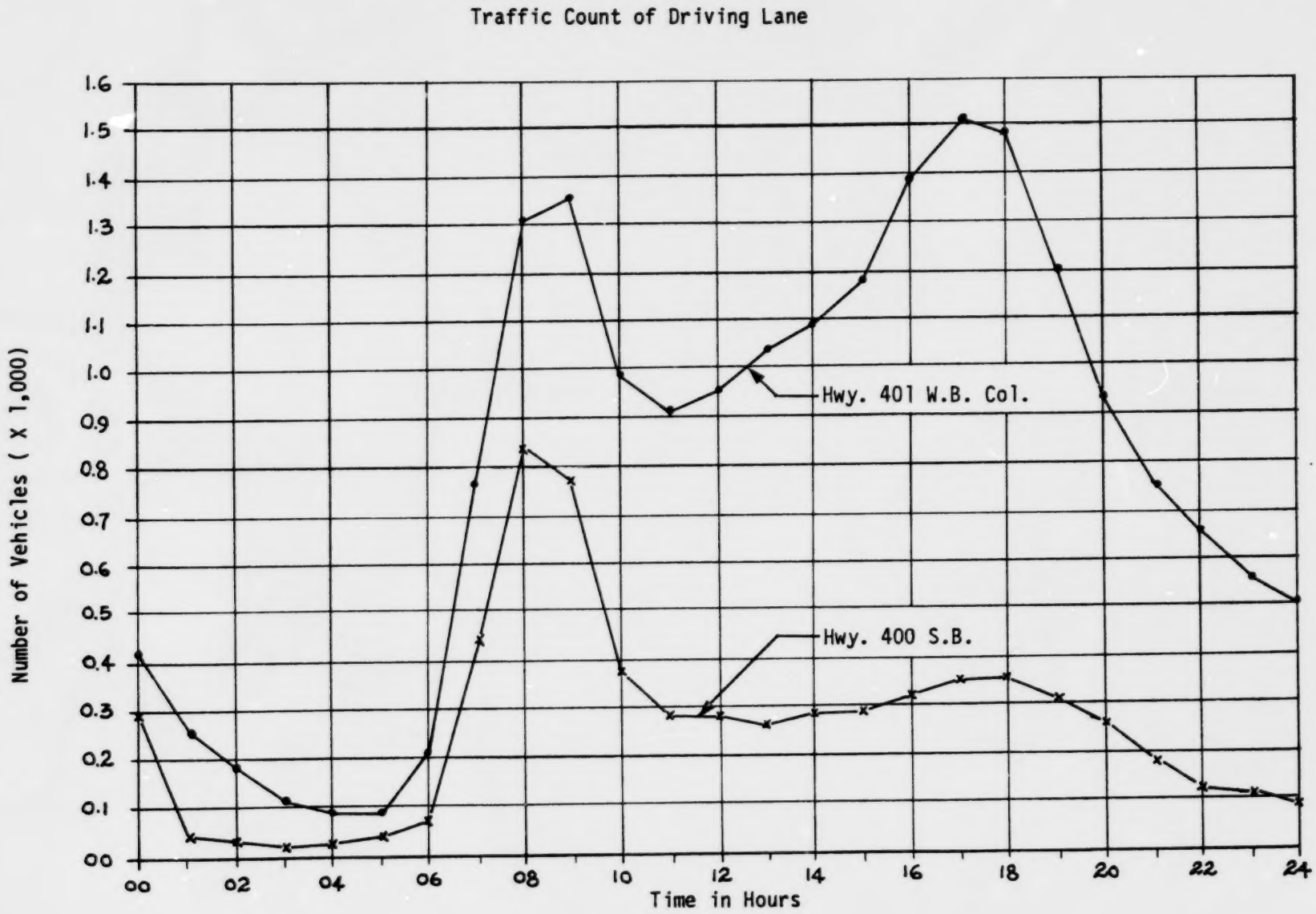


Figure 10 Typical Traffic Peak Hours on Hwys. 401 & 400 (1984 03 09)

6. CONCLUSIONS AND RECOMMENDATIONS

This study attempted to correlate the road surface temperature with traffic volumes, ambient air temperature, and solar radiation. The objective of this study could not be met with the experimental procedures used due to the range of error and a consequent lack of confidence in the results. There are too many variables which could not be quantified accurately with the data collected. The conclusions are in the form of general observations. The data were not reliable nor accurate enough to derive equations for calculating surface temperatures.

1. On a cloudy day, the pavement surface temperature will be close to the air temperature and varies in approximately the same amount as the air temperature.

2. On sunny days, the pavement surface temperature peaks in the early afternoon and is dependent on the amount of solar radiation received. If the same amount of solar radiation is received on two days, the peak temperature will be about the same. The pavement surface temperature will exceed the air temperature in a non-linear fashion.

3. There does not appear to be any correlation with traffic volumes and pavement surface temperature in the macro sense; however, a micro comparison of wheel track and centre of lane pavement temperatures is not possible due to the range of the system errors (up to $\pm 1.0^{o}C$).

4. If a day is sunny, the asphalt temperature will continue to be warmer than the air temperature the following night. This could not be quantified because the effects of the subgrade and other variables affecting the nighttime temperature were not evaluated. The higher

temperature is due to the pavement absorbing heat and storing it in the pavement structure where it will radiate back out to the pavement surface at night.

Based on an analysis of the test results, it appears that the instrumentation used in this study has not provided reliable data. The thermocouples used do not appear to have the accuracy to distinguish the small differences in pavement surface temperatures with which we are working. If further work is to be carried out along these lines, then an alternative method of monitoring pavement surface temperatures and air temperatures must be determined.

7. RECOMMENDED EXPERIMENTS

One major source of error is the unknown accuracy of the instruments and procedures used to measure surface temperatures. A series of lab tests are recommended to develop a practical and accurate method of measuring the surface temperatures in the field with a high level of reliability. It is proposed that tests be done on thermistors which are up to 400 times more sensitive than thermocouples. However, the thermistors are very delicate and require careful installation and protection, especially under field conditions.

The thermistors must be protected from traffic by being set slightly below the surface. The difference between the temperature at the depth at which the thermistor is placed and the actual surface temperature must be calibrated for simulated winter conditions. A method of protection and installation must be devised which does not introduce experimental error.

Frequency of sampling should also be established through laboratory experimentation. The lag response time of the thermistors to a change in surface temperature should be determined. This lag time would then be a lower limit to sampling frequency. The heat required to cause a temperature change could be provided by a sun lamp to simulate solar radiation or by friction to simulate tire action.

Experiments should be conducted on an asphalt sample placed in the cold room. The sample would have thermistors partially exposed in the manner proposed by Straub and at various depths throughout. The partially exposed thermistor will be used as the control, indicating the true surface temperature. The thermistors would be placed and sealed with various techniques and materials. Examples of possible areas of studies include the use of

copper tubes as heat sinks and protection and the use of thermal compounds in drilled holes.

Accurate data with frequent or continuous sampling is required to determine if traffic affects the asphalt temperature. This can be illustrated simply. Figure 11 shows gap time vs time of day. Gap time is defined as the span of time it takes for a following car to pass the same point as the lead car. Gap time decreases as volume increases in free-flowing traffic. It is anticipated that heat transferred from the tires to the pavement will be dissipated or radiated to the atmosphere within a short time period. This time period will be referred to as the critical gap time. The frequency of sampling should be less than the critical gap time. This is the upper limitation on sample frequency and may be determined through experimentation.

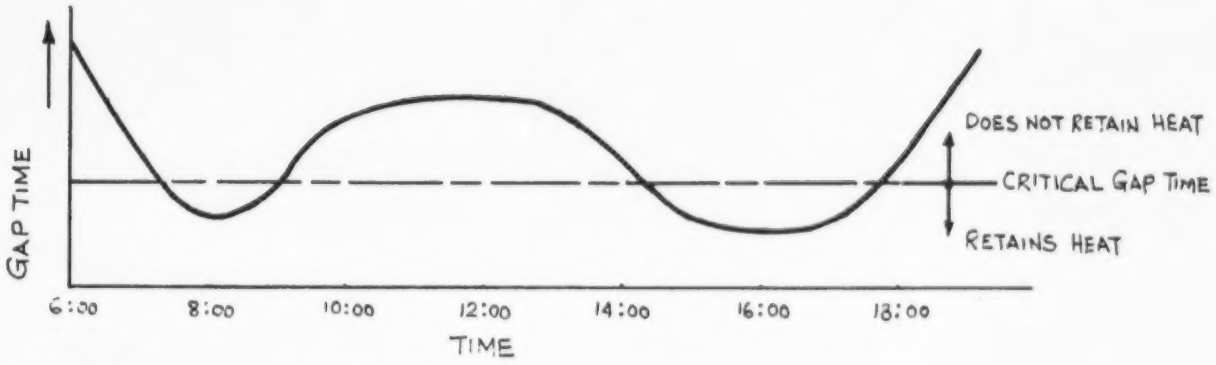
The lower limit on sample frequency will be the time constant. This is the time required for a precision thermistor to register 63.3% of the temperature change. This should be determined in the lab.

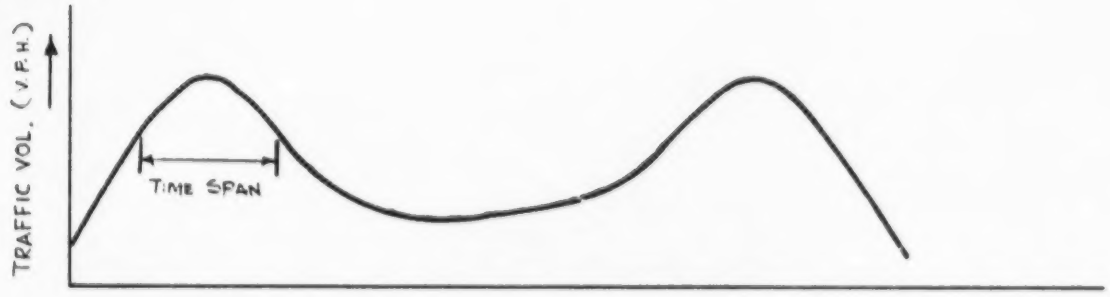
The data acquisition system should sample continuously taking the mode or mean of values over the critical gap time. This will avoid the problem of windowing, where a point sample once in 60 seconds does not provide information about the entire minute. The data acquisition system should be programmed to find the mode or mean temperature in the critical gap time and to store this on tape. Data would be required from three sensors in the road, air temperature, solar radiation, humidity, and traffic. Therefore, seven sensors would be used requiring 10,080 pieces of datum per week per site, or 40,320 data points per month per site. This large quantity of data must be stored on the data acquisition system on a magnetic

tape for dumping into a computer. This avoids the need for human processing of large volumes of data.

One possible alternative for reduced data processing would be less frequent sampling during non-peak traffic periods, such as at night. Another alternative would be to store data only when there is a temperature change registered. This will depend on the programming capabilities of the data acquisition system.

The effects of the subgrade on pavement surface temperatures could also be studied by placing thermistors or thermocouples at various depths below the pavement surface.





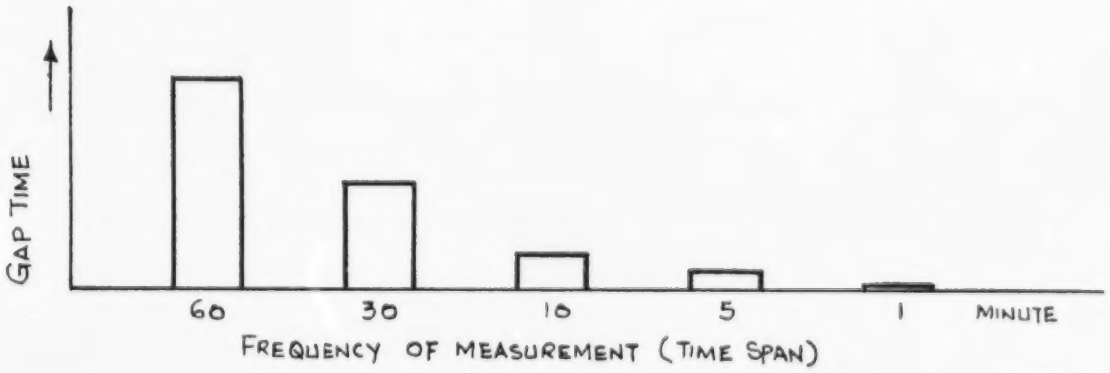


Figure 11 **Gap Time vs Time of Day**

8. FIGURES

Figure 1	Typical Site Layout for Thermocouples
Figure 2	Thermocouple Installation in Pavement
Figure 3	Heat Balance at the Pavement Surface (taken from Ref. (2))
Figure 4	Installation of Surface Probe (taken from Ref. (4))
Figure 5	Temperature Difference Between Wheel Track and Centre of Lane
Figure 6	Thermodynamic Relationship in Melting of Ice by Chemicals (taken from Ref. (5))
Figure 7	Phase Diagram for Water-Rock Salt (taken from Ref. (5))
Figure 8	Effect of Cloud on Solar Radiation Received
Figure 9a	Daily Pavement Temperatures - Low Solar Radiation (total 2.79 Mj/m^2/day)
Figure 9b	Daily Pavement Temperatures - Medium Solar Radiation (total 8.91 Mj/m^2/day)
Figure 9c	Daily Pavement Temperatures - High Solar Radiation (total 17.89 Mj/m^2/day)
Figure 10	Typical Traffic Peak Hours on Hwys. 401 & 400 (1984 03 09)
Figure 11	Gap Time vs Time of Day

9. TABLES

Table 1. Input Format for Dependend and Independent Variables

Table 2. Summary of Multiple Regression Analysis Results

Table 3. Temperature Difference Between Pavement and Ambient Due to Solar Radiation

10. REFERENCES

1. MTC Operating Instruction M-700-C, 'Winter Maintenance Operations During Winter Season'.

2. Noss, P.M., 'The Relationship Between Meteorological Factors and Pavement Temperatures', Symposium on Frost Action on Roads, Paris, 1973.

3. Gustafson, K., 'Icing Conditions on Different Pavement Structures', Transportation Research Record 860.

4. Straub, A.L., Schenck, Jr., H.N., and Przbycian, F.E., 'Bituminous Pavement Temperatures Related to Climate', Highway Research Record No. 256.

5. Minsk, L.D., 'Snow and Ice Properties Pertinent to Winter Highway Maintenance', Highway Research Record No. 94 (1965).

APPENDIX A

INDEPENDENT VARIABLE			CARD COL.	INDEPENDENT VARIABLE NAME
X_1	X_1'	X_1''	7-8	HOUR OF A DAY (1-24 HRS.)
X_2	X_2'	B	9	TRAFFIC DIRECTION (N=1, NE=2, E=3, ··· NW=8)
X_3	B	B	10	HWY. LOCATION (HWY. 401 = 1, HWY. 400 = 2, Q.E.W. = 3)
X_4	B	B	11	ROAD SURFACE (HWY. 401-O.F.C. = 1, HWY. 400-HL1 = 2, Q.E.W.-SLAG = 3)
X_5	B	B	12	ROAD TOPOGRAPHY (HWY. 401-URBAN = 1, HWY. 400-SUBURBAN = 2, Q.E.W. = 3)
X_6	X_3'	X_3''	38-41	TRAFFIC COUNT (TRAFFIC COUNT ON DRIVING LANE ONLY - HOURLY)
X_7	X_4'	X_4''	42	DAY (MON.=1, TUE.=2, ··· SUN=7)
X_8	X_5'	X_5''	43	WEEK DAYS AND WEEK END (MON. TO FRI. = 1, SAT. TO SUN. = 2)
X_9	X_6'	REP.	44-46	AIRPORT AIR TEMP. °C (HWY. - TORONTO ISLAND, HWY. 400 - INTERNATIONAL A. - HOURLY)
X_{10}	X_7'	X_6''	47-49	MAX. HUMIDITY % (BY DAILY)
X_{11}	X_8'	X_7''	50-51	MIN. HUMIDITY % (BY DAILY)
X_{12}	X_9'	X_8''	52-55	DEGREE-DAYS OF HEATING (BASE 18.0°C - BY DAILY)
X_{13}	B	B	56-58	DEGREE-DAYS OF GROWING (BASE 5.0°C - BY DAILY)
X_{14}	X_{10}'	X_9''	59-62	TOTAL PRECIPITATION mm (BY DAILY)
X_{15}	X_{11}'	X_{10}''	63-64	SNOW ON GROUND cm (BY DAILY)
X_{16}	X_{12}'	REP	65-68	BRIGHT SUNSHINE HRS. (BY DAILY)
X_{17}	X_{13}'	X_{11}''	69	PREDOMINANT WIND DIRECTION (SEE TRAFFIC DIRECTION CODE & CALM=0 - HOURLY)
X_{18}	X_{14}'	X_{12}''	70	SECONDARY WIND DIRECTION (SEE TRAFFIC DIRECTION CODE & CALM=0, - BY HOURLY)
X_{19}	X_{15}'	X_{13}''	71-72	WIND VELOCITY Km/h (BY HOURLY)
		X_{14}''	74-78	SOLAR RADIATION Megajoule/m²/h (HWY. 401 - CITY OF TOR. HWY. 400 - WOODBRIDGE)
		X_2''	13-17	EXPOSED AIR TEMP. °C (THERMOCOUPLE - BY HOURLY)

DEPENDENT VARIABLE			CARD COL.	DEPENPENT VARIABLE NAME
Y_1			13-17	EXPOSED AIR TEMP. °C (THERMOCOUPLE - BY HOURLY)
Y_2			18-22	MID DRIVING LANE TEMP. °C (THERMOCOUPLE - BY HOURLY)
Y_3			23-27	SHOULDER TEMP. °C (THERMOCOUPLE)
Y_4	Y_1'	Y_1''	28-32	WHEEL TRACK - DRIVING LANE TEMP. °C (THERMOCOUPLE - BY HOURLY)
Y_5			33-37	SHADED AIR TEMP. °C (THERMOCOUPLE - BY HOURLY)

CALCULATED DEPENDENT VARIABLE	SPECIAL DEPENDENT VARIABLE NAME
$Y_6 = [(Y_2) - (Y_4)]$	DELTA TEMP. 6 °C = [(MID-D.L. TEMP.) - (WHEEL TRACK - D.L. TEMP.)]
$Y_7 = [(Y_5) - (Y_1)]$	DELTA TEMP. 7 °C = [(SHADE AIR TEMP.) - (EXPOSED AIR TEMP)]
$Y_8 = [(Y_3) - (Y_2)]$	DELTA TEMP. 8 °C = [(SHOULDER TEMP.) - (MID-D.L. TEMP.)]

Table 1. Input Format for Dependent and Independent Variables

HWY.	TIME	MODEL	Y	X_1	X_2	, • • • ,	X_{19}	STD. DEV.	R^2	
HWY. 401 + HWY. 400	1984 JAN. 24 HRS.	$Y_1 = X_1 - X_{19}$	Y_1 -8.24	X_9 1.05	X_{11} 0.07	X_{14} 0.37		1.77	0.94	
		$Y_2 = X_1 - X_{19}$	Y_2 -7.34	X_9 0.96	X_{15} 0.12	X_{16} 0.28		1.70	0.93	
		$Y_3 = X_1 - X_{19}$	Y_3 -6.93	X_9 0.93	X_{16} 0.48	X_{17} -0.18		1.89	0.88	
		$Y_4 = X_1 - X_{19}$	Y_4 -6.85	X_9 0.84	X_{16} 0.35	X_{17} -0.17		1.64	0.91	
		$Y_5 = X_1 - X_{19}$	Y_5 -6.73	X_9 0.99	X_{16} 0.62	X_{17} -0.22		2.13	0.88	
		$Y_6 = X_1 - X_{19}$	Y_6 -0.50	X_9 0.12	X_{15} 0.17	X_{17} 0.28		1.27	0.59	
		$Y_7 = X_1 - X_{19}$	Y_7 1.51	X_{16} 0.25	X_{17} -0.24			1.42	0.52	
		$Y_8 = X_1 - X_{19}$	Y_8 0.41	X_2 -0.71 B	X_{15} -0.11	X_{16} 0.20	X_{17} -0.28	1.19	0.66	
HWY. 401	1984 JAN. 6:00 - 18:00 SOLAR HRS.	$Y_1' = X_1' - X_{15}'$	Y_1' -5.04	X_6' 0.89				1.82	0.87	
		$Y_1' = X_3'$	Y_1' -4.64					4.80	* 0.01	
		$Y_1'' = X_1'' - X_{14}''$	Y_1'' -5.41	X_1'' 0.33	X_2'' 0.33	X_8'' -0.45	X_{14}'' 2.15	0.88	0.97	
		$Y_1'' = X_2'' X_3'' X_{14}''$	Y_1'' -4.78	X_2'' 0.82				1.56	0.893	* ΔR^2 = 0.002
		$Y_1'' = X_2'' X_{14}''$	Y_1'' -4.78	X_2'' 0.82				1.57	0.891	
	1984 FEB. 6:00 - 18:00 SOLAR HRS.	$Y_1^* = X_1^* - X_{14}^*$	Y_1^* 4.39	X_1^* 0.34	X_2^* 0.48	X_{10}^* -0.10	X_{14}^* 2.30	1.13	0.96	
		$Y_1^* = X_2^* X_3^* X_{14}^*$	Y_1^* 4.10	X_2^* 0.87	X_3^* 0.002	X_{14}^* 1.21		1.78	0.901	* ΔR^2 = 0.018
		$Y_1^* = X_2^* X_{14}^*$	Y_1^* 4.10	X_2^* 0.86	X_{14}^* 1.09			1.94	0.883	
HWY. 400	1984 JAN. 6:00 - 18:00 SOLAR HRS.	$Y_1' = X_1' - X_{15}'$	Y_1' -5.14	X_6' 0.90				2.03	0.88	
		$Y_1' = X_3'$	Y_1' -4.85	X_3' -0.006				4.97	* 0.07	
		$Y_1'' = X_1'' - X_{14}''$	Y_1'' -4.98	X_1'' 0.42	X_2'' 0.74	X_{10}'' -0.21	X_{14}'' 2.74	1.18	0.96	
		$Y_1^* = X_2'' X_3'' X_{14}''$	Y_1^* -4.69	X_2'' 0.75	X_{14}'' 1.92			1.78	0.883	* ΔR^2 = 0.005
		$Y_1^* = X_2'' X_{14}''$	Y_1'' -4.69	X_2'' 0.77	X_{14}'' 2.41			1.82	0.878	
	1984 FEB 6:00 - 18:00 SOLAR HRS.	$Y_1^* = X_1^* - X_{14}^*$	Y_1'' 2.90	X_2'' 0.86	X_{14}'' 1.61			1.16	0.96	
		$Y_1^* = X_2^* X_3^* X_{14}''$	Y_1'' 3.26	X_2'' 0.83	X_3'' -0.003	X_{14}'' 1.66		1.55	0.914	* ΔR^2 = 0.010
		$Y_1^* = X_2'' X_{14}''$	Y_1^* 3.26	X_2'' 0.83	X_{14}'' 1.93			1.63	0.904	

NOTE : * DUE TO TRAFFIC

Table 2. Summary of Multiple Regression Analysis Results

DATE		84 01 24	84-01-26	84-01-17	84-02-03	84-03-07	84-03-08	84-03-09	84-03-10	84-03-11	84-03-12	84-03-13
TOTAL SOLAR RADIATION (MJm^{-2})		1.552	2.823	8.906	1.702	17.995 E	13.754	17.888	16.681	13.421	13.909	2.793
Hwy. 401	AVERAGE PAV'T. TEMP. °C	-0.7	-1.0	-1.3	4.2	0.8	0	2.8	5.5	-0.4	-0.8	-2.1
	EXP. AIR °C	0.7	-2.2	-2.3	3.5	-3.4	-8.5	-1.0	-1.8	-5.2	-8.2	-3.2
	DIFF. °C	1.4	1.2	1.0	0.7	4.2	8.5	3.8	7.3	4.8	7.4	1.0
Hwy. 400	AVERAGE PAV'T. TEMP. °C			-1.5	3.5	5.0	2.5	8.2	8.8	4.0 E	3.0 E	-2.8
	EXP. AIR °C			-5.1	2.6	-13.0	-8.2	-8.2	-5.1	-5.0 E	-5.0 E	-3.8
	DIFF. °C			3.6	0.9	18.0	10.7	16.4	13.9	9.0	8.0	1.0
Q.E.W.	AVERAGE PAV'T TEMP. °C			-0.5	4.8	7.0	-1.0	6.8	7.4	1.0	3.5	-1.0
	EXP. AIR °C			-3.1	2.2	-6.2	-9.8	-3.0	-4.0	-10.0	-9.5	-2.2
	DIFF. °C			2.6	2.6	13.2	8.8	9.8	11.4	11.0	13.0	1.2
AVERAGE DIFF. °C		1.4 *	1.2 *	2.4	1.4	11.8	9.3	10.0	10.9	8.3	9.5	1.1

NOTE: E = ESTIMATE

* = NOT AVERAGE

Table 3. Temperature Difference Between Pavement and Ambient Due to Solar Radiation